APPENDIX 9.A — HIGH-VELOCITY CULVERT

9.A.1 INTRODUCTION

At most locations, the conventional culvert is the appropriate choice. A conventional culvert with an improved inlet may be a more economical alternative at some locations that possess certain unique site characteristics as explained below. A high-velocity culvert with broken alignment may provide the most effective design at sites where the terrain is unusually steep.

9.A.1.1 <u>Location Considerations</u>

Because the inlet and outlet geometry are costly, it is essential that a location have specific geometric characteristics for a high-velocity culvert to be practicable. These characteristics would require that a culvert:

- be relatively long,
- have a significant differential between Elevations A and E (Figure 9.A-1), and
- operate in inlet control.

9.A.1.2 <u>Uses</u>

Locations having the required geometric location characteristics where a high-velocity culvert might prove appropriate are as follows:

- less costly,
- little or no backwater can be tolerated,
- high approach velocities should be perpetuated,
- minimize or eliminate upstream sediment deposition problems,
- provide a grade control structure,
- wildlife agencies need a rough fish barrier, and
- perhaps avoid flow conflicts with utilities.

Locations having geometric location characteristics where a high-velocity culvert might be inappropriate are as follows:

- Fish passage is required.

- Prospective contractors would be too inexperienced to construct the complex inlet and outlet.

9.A.1.3 <u>Computer Program</u>

At this time, there is no known software for designing a high-velocity culvert. There is software for stilling basin design (see Energy Dissipators Chapter).

9.A.2 GEOMETRY

High-velocity culverts have four distinct geometric parts: inlet, barrel, expansion and stilling basin (if required). The design of each part is related to the design of the remaining three parts, thus requiring a trial-and-error procedure. Figure 9.A-1 shows these parts and their interrelationship with each other.

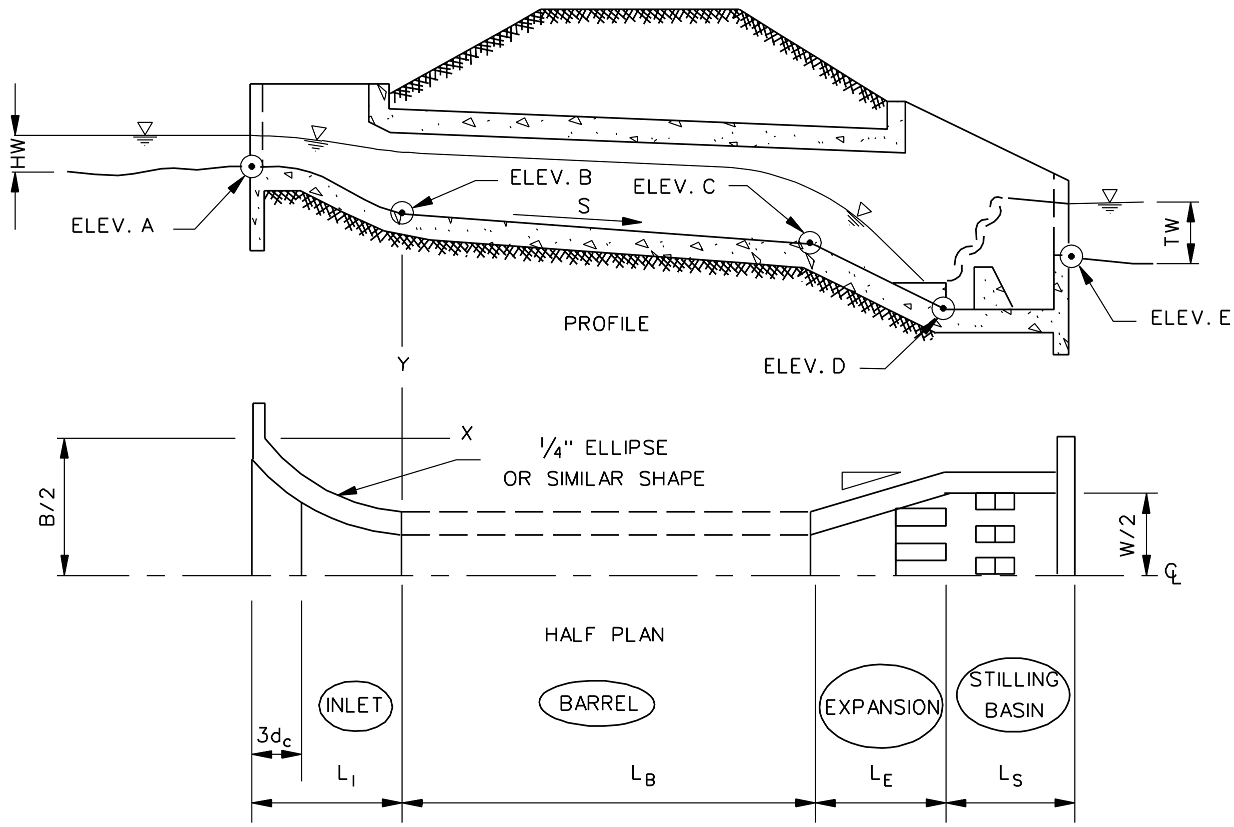

FIGURE 9.A-1 — High-Velocity Culvert

9.A.2.1 Inlets

Inlet walls are flared to generally conform to a quarter of an ellipse. As the inlet wall converges inward to meet the outside barrel walls, the inlet bottom drops to force a relatively straight water surface through the inlet. These walls should be constructed to conform to the predicted elliptical pattern preferred or the ellipse may be simulated by 1.5-ft tangents to facilitate construction. This simulated geometry will have a greater tendency to spawn standing waves at higher velocities and possibly adversely affect the inlet capacity.

The inlet is designed as a subcritical transition even though the velocities may be in the critical to low supercritical range. A trial-and-error procedure is used to arrive at the inlet bottom profile and water surface geometry. Sometimes, judgmental compromises in these geometries and perhaps the quarter ellipse wall criteria are required. The upstream inlet width is determined using a broad-crested weir equation and the approach hydraulic grade line, as constrained by any allowable backwater.

9.A.2.2 Barrel

The barrel size is determined using Manning's equation. As practicable, a square shape is preferable. It is also preferable to avoid having the design flood touch the top of the barrel because this results in better hydraulic efficiency, provides some drift freeboard and avoids potential pressure flow problems.

9.A.2.3 Stilling Basin

Once a sufficiently high Froude number is attained, it is necessary to force a hydraulic jump. This requires a stilling basin.

9.A.2.4 Expansion

Commonly, the more efficient high-velocity culverts will reach barrel velocities in excess of 18 ft/s to 20 ft/s. This frequently exceeds the ability of available flexible linings (e.g., riprap) or even wire-enclosed riprap to prevent serious outlet scour problems. When this occurs, it is necessary to provide a stilling basin. Although relatively high outlet velocities are frequently attained, seldom is the barrel Froude number sufficient for a reliable hydraulic jump. When this occurs, it is necessary to increase the Froude number by expanding the culvert barrel, increasing the velocity by greatly increasing the bottom slope through lowering of the stilling basin floor or both. The increased bottom slope may be in the form of an ogee shape as with an uncontrolled spillway on a dam, or a straight line as with chute-type geometry. With the straight-line geometry, it is necessary to ensure that the flow remains in contact with the bottom, however.

9.A.3 SEDIMENTATION

Because the barrel bottom is depressed, it is essential that consideration be given to potential sediment problems within the inlet and barrel. Sediment deposition is acceptable but only within certain limits. As a general rule, a culvert geometry should be selected that precludes deposition blocking the inlet. Assuming a relatively stable downstream channel, the sediment deposition in the culvert barrel should conform to that of Figure 9.A-2. Where a rigorous culvert sediment analysis is deemed advisable, the engineer should refer to Appendix 9.C. In addition, should it be known that the channel is very unstable and aggrading, a detailed channel geomorphology analysis should be made to preclude unexpected and adverse sedimentation problems.

9.A.4 DESIGN CRITERIA

High-velocity culverts may be used where conventional culverts with standard or improved inlets are more costly or less adaptable to the site conditions. When considering the use of a high-velocity culvert, the following criteria should be used:

- Where applicable, the design criteria from this Chapter shall apply.
- An assessment of potential sediment problems shall be a routine part of any high-velocity culvert analysis. In no instance shall more than half the vertical culvert dimension be blocked by expected deposited sediment.

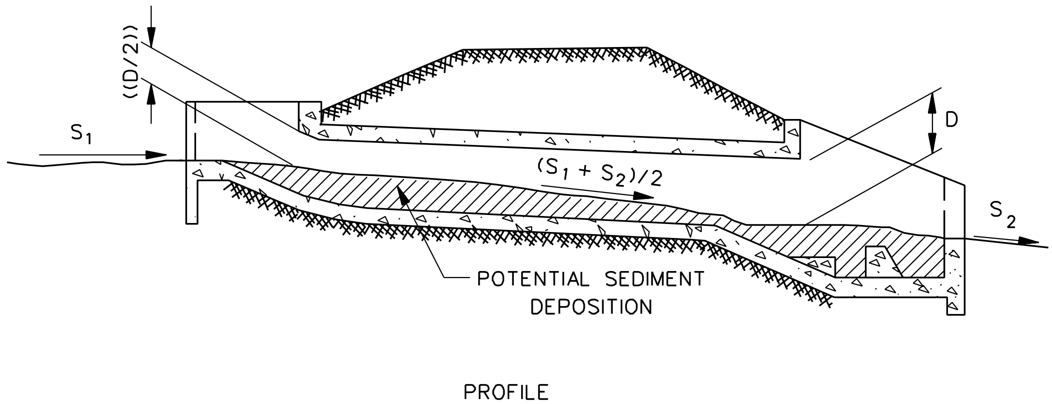

FIGURE 9.A-2 — Potential Sediment Deposition

- Expansions and stilling basins shall be used where outlet velocities exceed the ability of available channel protection methods to prevent channel scour that would cause unacceptable damage to highway facilities, downstream property or the environment.
- A high-velocity culvert shall not be used where a fishery is present unless approved by the responsible regulatory agency; if acceptable, a fish ladder or similar device may be used to offset adverse fish migration problems.
- A high-velocity culvert may be used as a channel grade control structure.
- Where more than one barrel is required, the intermediate walls shall be extended upstream to divide the approach flow equally between all barrels and to minimize flow disruption.
- Where the terminal velocity leaving the expansion and entering the stilling basin exceeds 30 ft/s, it shall be necessary to provide streamlined flow-splitter devices within the expansion to ensure an equal distribution of flow entering the full width of the stilling basin.
- The minimum box culvert size shall be 4 ft × 4 ft.
- Inlet and stilling basin cutoff walls shall be a minimum of 3 ft below the streambed.
- Flexible channel lining protection shall be provided at the inlet and outlet sufficient to accommodate the design flood. A filter shall be placed under the riprap where exfiltration of channel or bank material might occur.
- Velocities through the inlet may not be supercritical if the barrel velocity is subcritical.

9.A.5 GENERAL PROCEDURE

Before designing a high-velocity culvert, it is first necessary to obtain a drainage survey (see Data Collection Chapter) and the roadway template. After securing the survey, determine the flood-frequency relationship (see Hydrology Chapter) and the stage-discharge relationship (see Storage Chapter). To resolve sediment problems, it is helpful if an estimate of the sediment gradation curve, sediment transport rate and channel morphology (aggrading, degrading or stable) is obtained. The need for a grade-control structure or fish passage must also be ascertained prior to commencing the design.

Once the site data, hydrology, channel and channel morphology and economic analysis is completed, the design procedure consists of the following Steps. A trial-and-error process is required:

Step 1 PRELIMINARY BARREL SIZE. Determine through a conventional culvert analysis if a culvert would operate in inlet control. If inlet control occurs, use Manning's equation and, starting with a slope equal to approximately half that of the natural channel, determine a box size that is no more than approximately 90% full at the design flood. Keep the box as nearly square as practicable.

Select a trial structure geometry similar to that shown on Figure 9.A-1. The inlet length and embedment, expansion length and embedment and stilling basin length are only trial values at this point. With narrower boxes, embed a portion of the inlet and expansion under the roadway fill to reduce the culvert length — primarily a structural versus cost consideration.

Compute a TRIAL energy gradient through the TRIAL culvert geometry. If the TRIAL culvert geometry requires more energy than is available, increase the barrel size, number of barrels or stilling basin depression and repeat Step 1. Once an energy balance is obtained, the TRIAL improved culvert geometry is acceptable for further investigation.

Step 2 INLET DESIGN. Consider several TRIAL inlet geometries suggested by Figure 9.A-1 such as (1) elliptical walls with variable-sloped apron and straight-water surface, (2) variable-shaped walls with uniformly sloped apron and straight-water surface, and (3) elliptical walls with uniformly sloped apron and variable water surface. The inlet flare angle, θ, should not exceed $\mathrm{Tan}^{-1}[1/(3Fr)]$, but may be less. Plot the energy line and water surface through the inlet. Use the TRIAL energy loss from Step 1. If supercritical inlet flow occurs when subcritical TRIAL barrel flow exists, try adjusting the inlet geometry. If both supercritical inlet and TRIAL barrel flows occur, be cautious and use a relatively long inlet — a supercritical transition inlet design may be advisable depending on the maximum Froude number involved.

If unusual wall, floor or water surface geometry occur, try a longer inlet with less flare angle.

Compute the actual energy loss through the inlet based on the difference in velocity head. If the actual loss is the same or slightly less than the loss estimated in Step 1, the TRIAL culvert geometry is acceptable for further investigation. If not, return to Step 1.

Step 3 EXPANSION. Determine the outlet velocity and Froude number of the barrel. If the velocity is much greater than say 15 ft/s, a stilling basin should be considered. If a stilling basin is deemed necessary and the Froude number is much less than 4.5, an expansion should be considered.

From Step 2, use the actual energy loss through the inlet and recompute the energy gradient through the culvert.

Assume a TRIAL stilling basin depth. Assume an expansion loss of say 15% (85% recovery of energy). Compute the energy grade line through the expansion.

Determine a sequent depth for the hydraulic jump. If the tailwater depth plus the TRIAL stilling basin depth are the same or slightly less (10%±), then proceed with the assumed geometry; if not, assume a new TRIAL stilling basin depth and repeat the foregoing process. A significant change in the assumed TRIAL stilling basin depth may necessitate returning to Step 1.

From continuity, compute the required stilling basin width, which is also the downstream width of the expansion. Given this width and a selected flare angle, compute the expansion length. Extremely high velocities (> 30 ft/s) may necessitate a high-velocity expansion design requiring reverse curved walls and a small flare angle (costly). Commonly straight walls are used and some compromise is made in the flare angle to reduce the length (and thus cost) of the expansion. Such compromises must be evaluated to identify the potential risks being assumed.

Consider a variable-sloped (ogee shape) apron and a uniformly sloped apron. Use the variable sloped apron if significant flow separation is found to occur on the uniformly sloped apron. It may be necessary to adjust the variable slope apron length to obtain the foregoing computed width at the downstream end of the expansion.

Step 4 FINAL DIMENSION CHECK. Evaluate whether the dimensions and energy losses computed in Steps 1-3 agree with the energy available at the site. If not, return to Step 1; if all dimensions are compatible with the site and the energy balances, proceed with the outlet design.

Step 5 OUTLET DESIGN. Design an outlet to prevent unacceptable scour or erosion.

Step 6 SEDIMENT ASSESSMENT. From the initial channel morphology studies, assess whether expected sediment deposition, if any, will be a problem. If a problem is expected, return to Step 1 and adjust the TRIAL geometry.

9.A.6 EXAMPLE

This Example demonstrates the trial-and-error procedure required to design a high-velocity culvert with subcritical inlet. Survey data and flood-frequency relationships are assumed to have been obtained. Unique environmental considerations, roadway geometry, structural constraints and channel sediment and morphology characteristics are also assumed to be known.

9.A.6.1 Design Data

The designer will require Site Data, a Hydrology Analysis, an Upstream and Downstream Channel Analysis and perhaps an Economic Assessment.

9.A.6.2 Site Data

Site data includes the following:

- Recently constructed upstream property limits the allowable headwater, AHW, to 5.5 ft.
- Within the past ten years, the stream has developed a high sediment transport rate, which has caused frequent blockage of the existing culverts. This results from deposition due to temporary ponding during most runoff periods.

- A channel change downstream will provide approximately a 10-ft elevation difference through the culvert.
- Downstream land use dictates the need for an additional 200 ft (±) culvert length.
- The culvert length is to accommodate the roadway sections shown on Figure 9.A-1. *Note: Culvert dimensions and elevations shown on Figure 9.A-1 are those to be determined in this Example problem.*
- A recent meander cutoff has occurred downstream and a headcut is migrating upstream.

9.A.6.3 Hydrology Analysis

The selected design discharge, Q, from the hydrology analysis is 1380 ft^3/s. The dominant channel discharge was estimated as 350 ft^3/s (Reference *(1)*, Section 9.A.7), and the mean annual discharge was estimated as 250 ft^3/s.

9.A.6.4 Upstream Channel Analysis

From an upstream channel analysis, the following was determined:

- Average velocity for the design discharge, $V_n = V_1 = 5.7$ ft/s.
- Flow depth for the design discharge in main channel, $d_n = d_1 = 5.0$ ft.
- Dominant channel width is approximately 35 ft.
- Dominant flow depth is approximately 2.5 ft.
- Mean annual flow depth is approximately 2 ft.
- There is some overbank flow.
- Drift and debris consists of brush.
- Channel shows evidence of serious instability — bank caving and braiding. This is probably related to a downstream headcut and unstable upstream slope, S_1, of 0.036 ft/ft.
- The channel flow is subcritical.
- Bed and bank material is very erodible at velocities in excess of approximately 2 ft/s.

From a downstream channel analysis and site visit, the following was determined:

- Headcutting from a meander cutoff is occurring downstream.
- A channel morphology analysis indicated the expected regime slope is flatter than the aforementioned meander cutoff slope. This expected regime slope was found to be similar to the slope in stable reaches of the natural channel downstream from the cutoff or S_2 = 0.0026 ft/ft.
- The downstream channel cutoff will be reconstructed to the regime slope.

- This channel reconstruction will result in a streambed profile difference at the site of approximately 10 ft.
- A channel analysis indicates the average downstream velocity $V_n = V_7 = 6.8$ ft/s.
- Flow width of the dominant channel in stable reaches of this channel was determined to be 35 ft. This also is equal to the predicted stable dominant channel width.
- For the apparent regime slope and a stable channel geometry, the flow depth, $d_n = d_7 = 4.2$ ft/s.
- The flow is subcritical.
- The stable channel bed is very erodible at velocities greater than 2 ft/s. There is no underlying bedrock to limit culvert-induced scour.

9.A.6.5 Economic Assessment

An economic assessment was deemed necessary. The results were:

- the cost difference between (1) conventional multi-barrel or improved inlet culverts capable of perpetuating the sediment transport, (2) a bridge* with grade-control structure, and (3) a high-velocity culvert favored the latter; and
- structural engineers requested that the maximum clear span at the parapets of any culvert not exceed 15 ft.

**The bridge alternative is also not compatible with land-use requirements downstream.*

9.A.6.6 Preliminary Barrel Size

Based on the roadway template and downstream land-use requirements, a TRIAL barrel length, L_B, of 370 ft ($\pm$) and a TRIAL barrel size of 10 ft × 10 ft is selected.

Select a 9 ft barrel flow depth, d_2 and d_3, to pass debris, avoid potential submerged flow problems and reduce friction losses.

9.A.6.7 Hydraulic Properties

Compute the TRIAL Hydraulic Properties for Section 3.

Select trial flow depth, $d_3 = (0.9)(10.0) = 9$ ft. *Note: A more conservative designer concerned with supercritical flow may wish to select a greater depth and box width.*

Area, $A_3 = (9)(10.0) = 90 \text{ ft}^2$
Wetted Perimeter, $P_3 = 9 + 9 + 10 = 28$ ft
Hydraulic radius, $R_3 = A_3/P_3 = 90/28 = 3.21$ ft or $R^{2/3} = 2.18$ ft
$V_3 = Q/A_3 = 1380/90 = 15.33$ ft/s
$V_3^2/2g = (15.33)^2/((2)(32.2)) = 3.65$ ft

The low tailwater will allow the flow to pass through critical depth, or more likely, through a depth equal to 0.715 d_{c5} at the culvert outlet. Assuming this as the worse case should a stilling basin not be used, then:

$d_{c5} = 0.315[Q/B)^2]^{1/3}$
$d_{c5} = 0.315[(1380/10.0)^2]^{1/3} = 8.41$ ft
$0.715d_{c5} = (0.715)(8.41) = 6.01$ ft
$V_{c5} = 1380/((10)(6.01)) = 22.96$ ft/s

Because of this potentially high-outlet velocity, the extreme erodibility of the streambed/banks and the sensitivity of the site, it is decided to use a rigid stilling basin for the outlet rather than flexible channel lining as scour protection:

$Fr_3 = V_3 /(gd_3)^{1/2} = 15.33/((32.2 \times 9))^{1/2} = 0.9$ — subcritical

Select $n_{3\&4} = 0.014$. *Note: A more conservative designer might wish to select a higher value to ensure an adequate estimate of friction losses keeping in mind that an excessively high value may result in unexpected supercritical flow in the barrel*:

$S_{f3-4} = [V_3 n_3 / 1.486\, R_3^{2/3}]^2$
$S_{f3-4} = [((15.33)(0.014))/(1.486 \times 2.18)]^2 = 0.0044$ ft/ft
Required Energy, H_3, is $d_3 + V_3^2/2g = 9 + 3.65 = 12.65$ ft

9.A.6.8 <u>Geometry</u>

Assume a trial culvert geometry and check the energy balance. From Figure 9.A-1, verify that sufficient energy is probably available:

Available energy = Elev 110.52 – Elev 96.03 = 14.49 ft

Note: By placing the outlet below the streambed by an amount equal to the expected stilling basin depression below streambed at Section 6, an additional amount of energy would be available. This will probably result in a smaller TRIAL barrel size than selected in this problem. However, to avoid potentially serious sediment problems inherent at this site, the outlet flow line elevation at Section 5 will be held at the streambed elevation. This also allows this problem to illustrate an expansion design having a sloped floor.

Required energy is:

Friction loss, $h_{3-4} = (S_{f3-4})(L_{3-4}) = h_{3-4} = (0.0044)(370 \text{ ft}) = 1.63$ ft
Required energy, $H_2 = 12.65$ ft

* Inlet loss, $h_I = 0.1\, V_3^2 / 2g = 0.1(3.65) = 0.37$ ft
Total Required Energy ($\pm$) = 14.65 ft

The 14.65 ft required is approximately equal to the 14.49 ft available; therefore, it is OK to proceed with TRIAL size and geometry of Figure 9.A-1 below as actual inlet loss* will be found to be less than the preliminary loss that was roughly estimated on this first check.

It may be helpful at this time to plot the preliminary energy line similar to that shown in Figure 9.A-11 so as to better understand this design practice. *Note: Figure 9.A-9 reflects the expected final entrance loss of 0.2 ft as computed later during the inlet design rather than the preliminary entrance loss that could only be conservatively estimated at this time as 0.4 ft.*

9.A.6.9 Inlet Design

Because the barrel is flowing subcritical, design the entrance like a subcritical transition and so that it does not become supercritical; see Figure 9.A-2. Two entrance geometries will be considered; there could be others. The entrance design in itself may also be a TRIAL process.

9.A.6.10 Contraction Angle

The inlet contraction angle should not exceed Tan θ = 1/(3Fr). Because the maximum Fr for the inlet is 1.0, compute $\theta_{2\text{-}3} = \text{Tan}^{-1}\,[1/(3 \times 1)] = 18.4^{o}$ (maximum angle).

To be conservative, select $\theta_{2\text{-}3} = 12.5^{o}$ because this is a value sometimes recommended for subcritical transitions without splitter walls.

9.A.6.11 Length and Width

Compute the TRIAL inlet length and widths shown in Figure 9.A-1.

LENGTH. Select a coefficient of 3.087 for the broad-crested weir equation and a TRIAL H_o = 4.5 ft, which is less than the AHW of 5.5 ft. Let H_o be the weir depth at Section 1 and, for now, ignore inlet losses due to the contraction caused by the overbank flow identified in the Design Data:

$$Q = 3.087\ B_2 H_o^{1.5}$$
$$\text{Trial } B_2 = Q/(3.087\ H_o^{1.5}) = 1380/((3.087)(4.5^{1.5}))$$
$$B_2 = 47 \text{ ft}$$
$$\text{Trial } L_I = 47/\text{Tan } 12.5^{o} = 212 \text{ ft}$$

Length appears a little uneconomical, but the inlet can be embedded partially under the fill until the span at the parapet exceeds 15 ft as noted in the Design Data.

WIDTH. The trial width, B_2, exceeds the dominant channel width of 35 ft × 12 ft, which is less desirable than matching this width; perhaps a necessary compromise depending upon the remaining inlet design. Because there is some flow contraction, estimate the potential backwater, BW, above H_o. As a worse case, assume the flow reaches critical depth at the rectangular shaped inlet, Section 2:

$$d_{c2} = d_2 = 0.315\ [Q/B_2)^2]^{1/3}$$
$$d_{c2} = 0.315\ [(1380/47)^2]^{1/3} = 2.99 \text{ ft}$$
$$V_{c2} = V_2 = Q/(B_1 d_1) = 1380/(47 \times 2.99) = 9.82 \text{ ft/s}$$
$$V_{c2}^2/2g = 9.82^2/((2)(32.2)) = 1.50 \text{ ft}$$

Assume an entrance loss coefficient of K = 0.5.

Entrance loss = BW = $KV_{c2}^2/2g$ = say (0.5) (1.50) = 0.75 ft

Recompute H_o using trial B_2 = 47 ft

$H_o = [Q/(3.087\ B_2)]^{2/3} = [1380/((3.087)(47))]^{2/3} = 4.49$ ft

Potential upstream pond depth is then H_o + BW or:

4.49 + 0.76 = 5.25 ft, which is less than the AHW of 5.5 ft: OK to proceed with the inlet design.

In selecting the TRIAL barrel size, an assumed energy loss of $0.1V_3^2/2g = 0.37$ ft was used. Recompute the inlet energy loss more accurately based on the difference in velocity heads.

Inlet loss, $h_I = 0.1(V_3^2/2g - V_2^2/2g)$

$h_I = 0.1(3.65 - 1.50) = 0.22$ ft

Because 0.22 ft is less than but relatively close to the assumed 0.37 ft, it is OK to proceed with the inlet design. A big difference would have suggested a slightly smaller barrel size should be tried.

9.A.6.12 Geometry Considerations

Two inlet geometries ((shall)) be considered. The first alternative has a variable-sloped apron. This geometry has a predetermined wall shape and a uniform sloping water surface and, as such, commonly results in a variable-sloped apron.

The second alternative has a uniformly sloped apron. This geometry will again have a uniform sloping water surface and, as such, will result in the required wall shape.

As noted earlier, the inlet velocities cannot become supercritical, or an unexpected hydraulic jump may occur. Both alternatives will use the previously computed energy loss of 0.25 ft.

9.A.6.13 Variable-Slope Apron

The selected wall shape shall conform to a quarter ellipse. Based on the general ellipse equation, the inlet bottom width at various L_{In} points (Figure 9.A-2) would be defined by:

$$L_{In}^2/L_I^2 + [(B_2 - B_{In})/2]^2/(B_2 - B_3/2)^2 = 1$$

$$L_{In}^2/(80)^2 + [(45 - B_{In})/2]^2/(45 - 10.0/2)^2 = 1$$

$$B_{In} = 45 - [1225(1 - L_{In}^2/L_{12})]^{1/2}$$

Divide the inlet into say eight segments as shown on Figure 9.A-4. Plot the water surface and energy grade line assuming a uniform change between Sections 2 and 3 as shown later on Figure 9.A-5. Compute the flow depth, d_{In}, at each segment using the energy relationship:

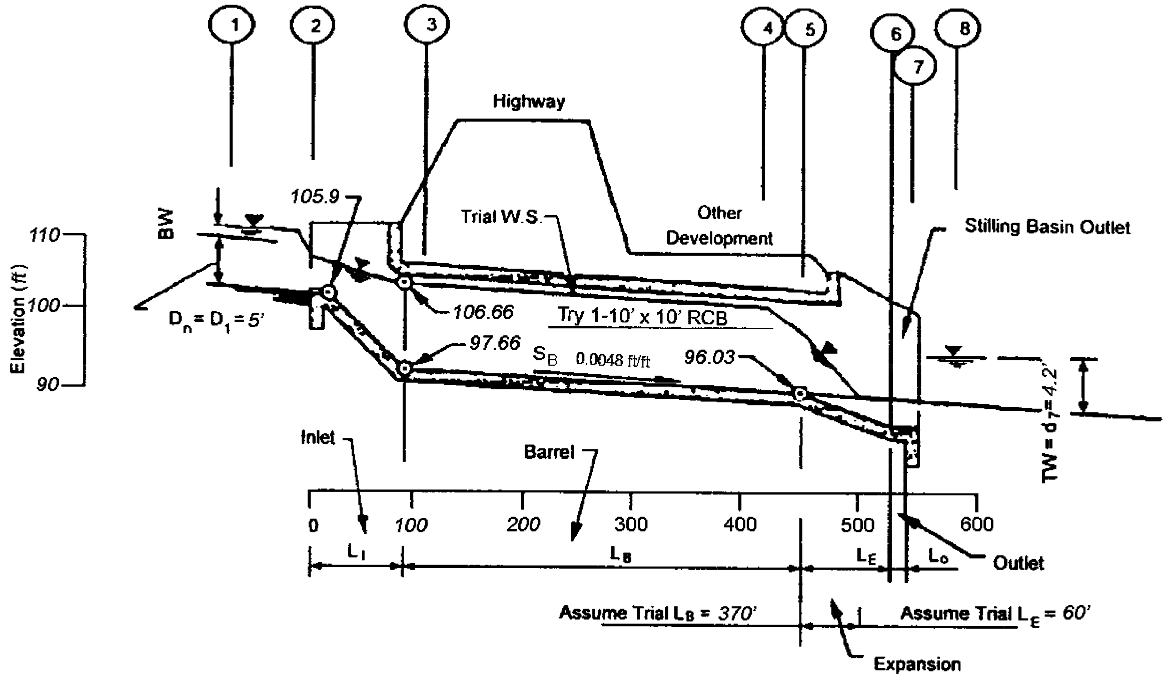

FIGURE 9.A-3 — Trial Geometry

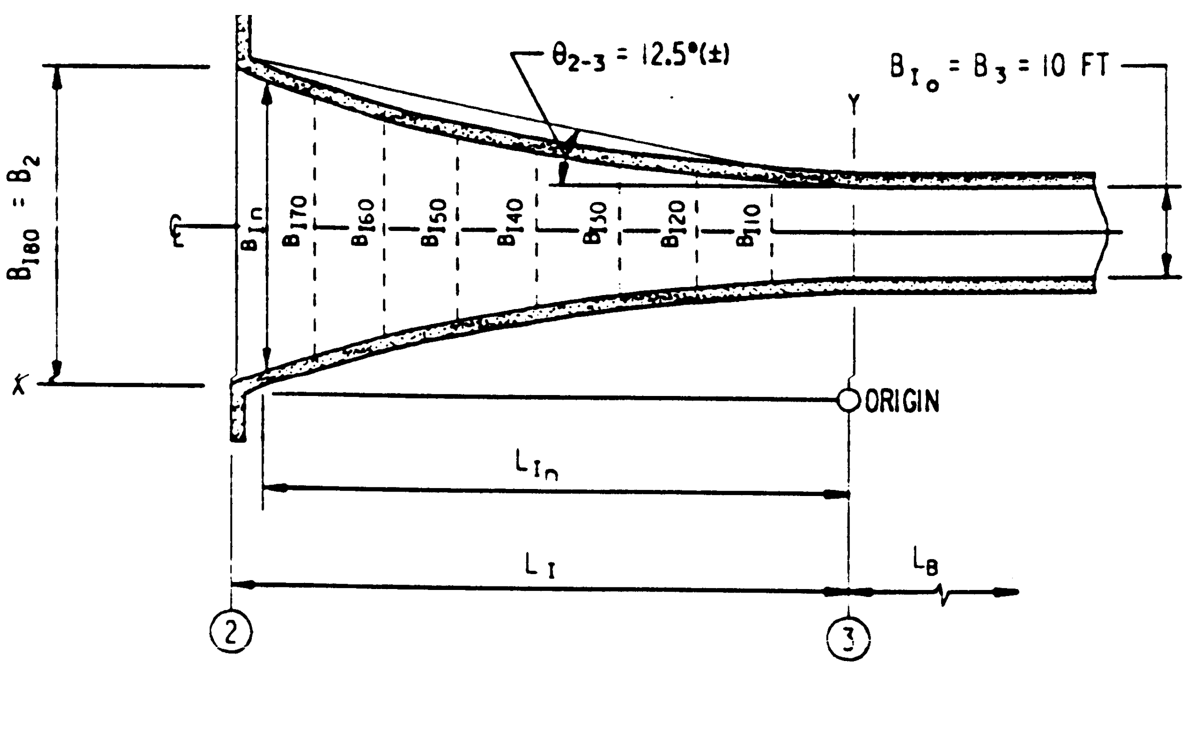

FIGURE 9.A-4 — Generalized Plan View For Trial Inlets

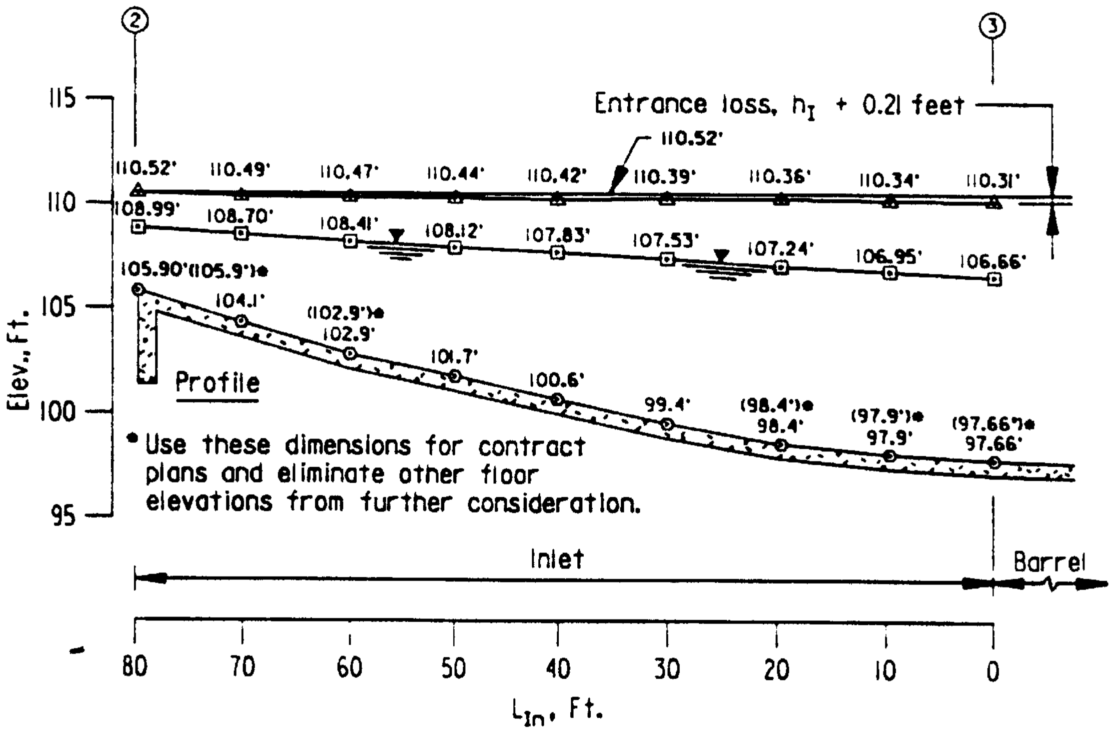

FIGURE 9.A-5 — Variable-Sloped Apron Inlet

TABLE 9.A-1 — Variable-Sloped Apron Inlet

L_{In} (ft)	B_{In}[*1] (ft)	Elev** (ft)	d_{In} (ft)	Bottom El (ft)	V_{In} (ft)	Fr_{In} (ft)
0	10.00	3.65	9.00	97.66	15.3	0.90
10	10.33	3.39	9.00	97.90	14.8	0.87
20	11.08	3.12	8.80	98.40	14.1	0.84
30	12.50	2.86	8.10	99.40	13.6	0.84
40	14.67	2.59	7.30	100.60	12.9	0.84
50	17.67	2.32	6.40	101.70	12.2	0.85
60	21.83	2.06	5.50	102.90	11.5	0.86
70	28.00	1.79	4.60	104.10	10.7	0.88
80	45.00	1.53	3.09	105.90	9.9	0.99

*1 Width adjusted to even inches to facilitate contract plan preparation and construction.

*2 Elevation Energy Grade line – Elev W.S.

$$h_{In} = V_{In}^2/2g + d_{In}, \text{ or}$$
$$d_{In} = Q/[2gB_{In}^2(\text{Elev Energy Grade Line} - \text{Elev W.S.})]^{1/2}$$

Compute the hydraulic properties at each segment to ensure flow remains subcritical. Enter the findings in Table 9.A-1.

To illustrate, consider $L_{In} = (L_{In})_{30} = 30$ ft

$$(B_{In})_{30} = 45 - [1225\,(1 - (30^2/80^2)]^{1/2} = 12.5 \text{ ft}$$
$$(d_{In})_{30} = 1380/[(2)(32.2)(12.5^2)(110.39 - 107.53)]^{1/2} = 8.13 \text{ ft}$$

Inlet floor elevation = 107.53 – 8.13 = 99.40 ft

$$(V_{In})_{30} = 1380/((8.13)(12.6)) = 13.47 \text{ ft/s}$$
$$(Fr_{In})_{30} = 13.47/((32.2)(8.13))^{1/2} = 0.83 \text{ — subcritical: OK}$$

Compute the remaining apron elevations as shown in Table 9.A-1.

Plot the bottom elevation on Figure 9.A-5 to ensure there are no significant shape irregularities. The bottom shape can be simplified some to facilitate contract plan preparation and construction by employing four tangent sections using only those elevations shown in parentheses. If the bottom shape had been highly irregular, a longer inlet (L_B) would have been investigated.

Plot the inlet wall shape as shown on Figure 9.A-7 to help in selecting the best wall geometry for the contract plans and construction. Figure 9.A-7 suggests that the use of four tangents would simplify the contract plans and facilitate construction.

The variable-sloped apron inlet is acceptable because (1) the floor is regular in shape and relatively easy to construct, (2) the flow is subcritical throughout the inlet, and (3) the velocities are sufficiently high as to discourage sediment deposition during higher flows — at least through the upper end of the inlet.

9.A.6.14 Uniformly Shaped Apron

To perhaps better facilitate contract plan development and construction, consider an inlet having a uniformly sloped apron. With the uniformly sloped apron, again use the energy relationship, only this time to compute the required apron B_{In}:

$$h_{In} = V_{In}^2/2g + d_{In} = Q^2/[(d_{In}B_{In})^2\ 2g] + d_{In}$$
$$B_{In} = Q/[d_{In}\,(2g)^{1/2}\,(h_{In} - d_{In})^{1/2}]$$
$$h_{In} = \text{Elev Energy Grade Line} - \text{Elev Apron}$$

Again, divide the inlet into say eight segments and plot the water surface, energy grade line and apron — similar to Figures 9.A-3, 9.A-4 and 9.A-5.

Compute the required bottom widths, B_{In}, based on a uniformly sloped water surface and apron.

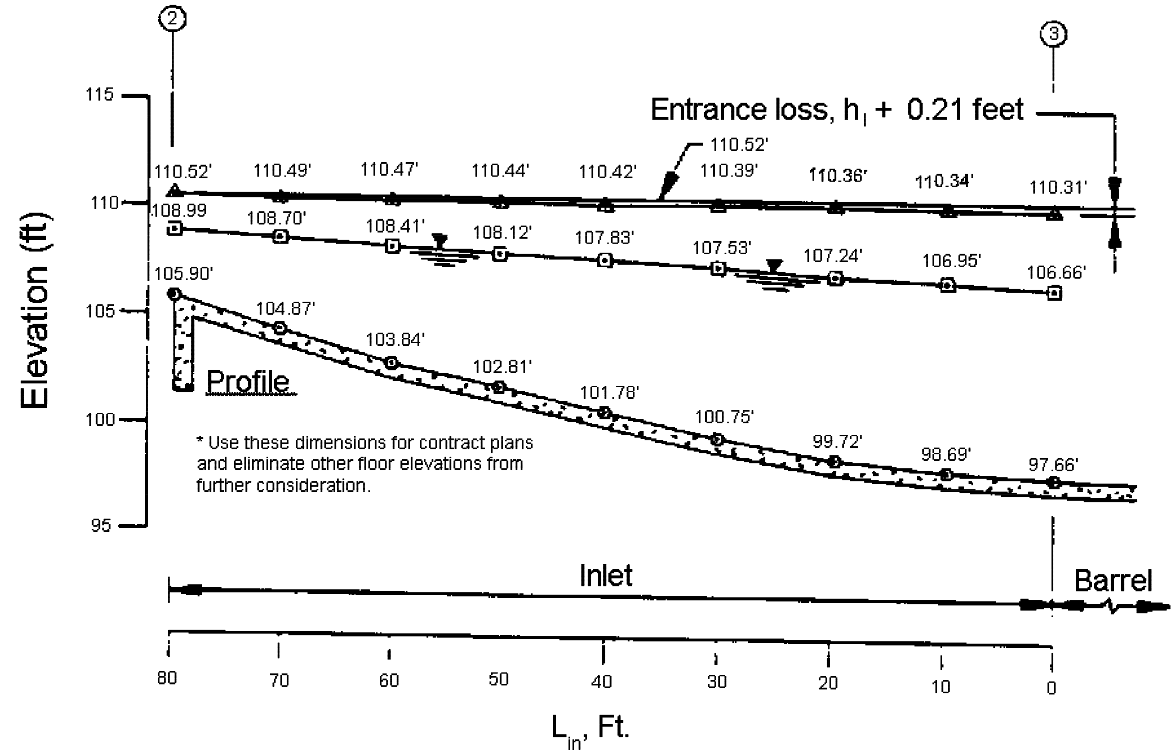

FIGURE 9.A.6 — Uniformly Sloped Apron Inlet

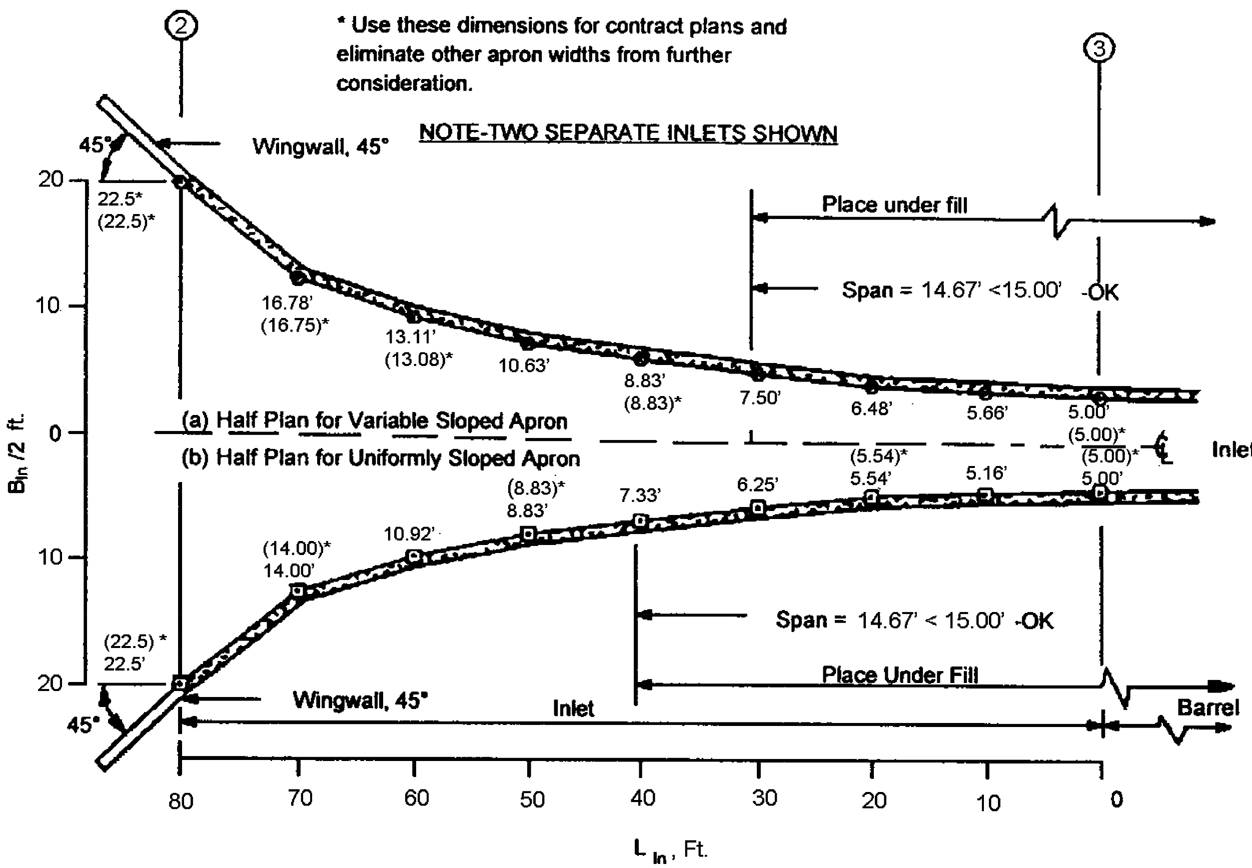

FIGURE 9.A-7 — Inlet Wall Shape

To illustrate, consider $L_{In} = (L_{In})_{30} = 30$ ft:

$(d_{In})_{30} = 107.53 - 100.75 = 6.78$ ft

$(B_{In})_{30} = 171.96/[110.39 - 100.75 (6.78^2 - 6.78^3)]^{1/2} = 15.00$ ft

$(Fr)_{9.14} = 13.57/((32.2)(6.78))^{1/2} = 0.92$ — Subcritical: OK

Compute the remaining apron widths as shown in Table 9.A-2.

TABLE 9.A-2 — Uniformly Sloped Apron Inlet

L_{In} (ft)	B_{In}[1] (ft)	Elev[2] (ft)	d_{In} (ft)	Bottom El (ft)	V_{In} (ft/s)	Fr_{In}
0	10.00	3.65	9.00	97.66	15.3	0.90
10	10.33	3.39	9.00	97.90	14.8	0.87
20	11.08	3.12	8.80	98.40	14.1	0.84
30	12.50	2.86	8.10	99.40	13.6	0.84
40	14.67	2.59	7.30	100.60	12.9	0.84
50	17.67	2.32	6.40	101.70	12.2	0.85
60	21.83	2.06	5.50	102.90	11.5	0.86
70	28.00	1.79	4.60	104.10	10.7	0.88
80	45.00	1.53	3.09	105.90	9.9	0.99

Plot the inlet wall shape as shown on Figure 9.A-7 to determine whether any shape irregularities occurred. An irregular-shaped wall would suggest the need to try a longer inlet. As suggested on Figure 9.A-7, use four tangents to simplify the contract plans and facilitate construction.

The uniformly sloped apron inlet is acceptable because (1) the walls are regular in shape and relatively easy to construct, (2) the flow is subcritical throughout the inlet, and (3) the velocities are sufficiently high as to discourage sediment deposition through the upper end of the apron during larger flows.

9.A.6.15 Expansion Design

Using the actual energy loss through the inlet of 0.21 ft versus the preliminary loss of 0.37 ft, plot the energy line from the inlet to the beginning of the expansion as shown in Figure 9.A-8. The energy near the beginning of the expansion at Section 4 is $H_4 = 108.68 - 96.03 = 12.65$ ft. This energy will be increased by whatever amount, h_4, a stilling basin apron must be depressed below the streambed.

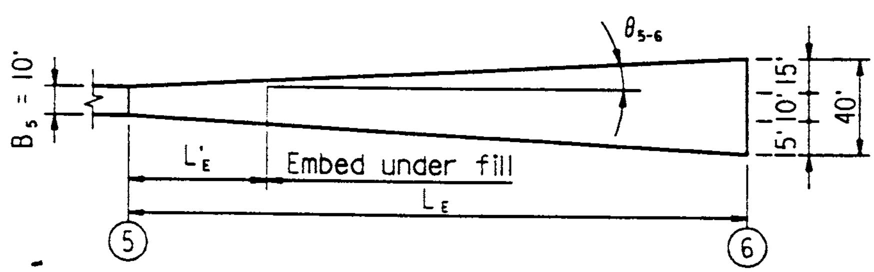

FIGURE 9.A-8 — Expansion Plan View

$Fr_3 = Fr_4$ of the barrel was previously computed as 0.9, which is inadequate for any hydraulic jump. Possibly, the previously computed outlet velocity of 22.96 ft/s could be controlled with a flexible channel lining. However, again assuming the potential risk is unacceptable, select a rigid outlet protection (stilling basin). Assume a USBR Type III stilling basin is selected that requires a $4.5 < Fr_6 < 9.0$ to obtain an effective jump (see Energy Dissipator Chapter).

9.A.6.16 Trial Basin Depth

Before the expansion can be designed, some stilling basin design must first be completed.

First assume a TRIAL stilling basin, h_4 (Figure 9.A-13) of 3.00 ft that must be added to the energy available at the stilling basin entrance.

Assume 85% of the energy available at Section 4 (a short distance upstream of the beginning of the expansion) is recovered at the end of the expansion, which is the entrance to the stilling basin. To select the expansion geometry, ignore the possibility that flow may reach critical depth or less as it enters the expansion. Energy at the stilling basin entrance would then be:

$$H_6 = 0.85\,(d_4 + V_4^2/2g + h_4) \qquad (9.A.1)$$

$$H_6 = 0.85\,(12.65 + 3.00) = 13.30 \text{ ft}$$

Also, for economy, select $Fr_6 = 4.5$ so that with:

$$Fr_6 = V_6/(gd_6)^{½} = 4.5 \qquad (9.A.2)$$

Combining Equations (9.A.1) and (9.A.2):

$$H_6 = 0.85\,(d_6 + [4.5(gd_6)^{1/2}]^2/2g + h_4) = 13.30 \text{ ft}$$

$$d_6 + 10.13\,d_6 = 13.30\text{, or}$$

$$d_6 = 13.30/11.13 = 1.19 \text{ ft}$$

$$V_6 = Fr_6(gd_6)^{½} = 4.5((32.2)(1.19))^{½} = 27.86 \text{ ft/s}$$

Checking:

$$H_6 = d_6 + V_6^2/2g = 1.19 + 27.86^2/((2)(32.2)) = 12.07 < 13.6 : \text{ OK}$$

9.A.6.17 Sequent Depth

First, compute a TRIAL stilling basin depth. The selected TRIAL stilling basin depth, h_4, plus the expected tailwater depth identified in the Design Data, TW = 4.20 ft (Figure 9.A-13), must be equal to or perhaps slightly greater than the required sequent depth, d_7, for a hydraulic jump having a $Fr_6 = 4.5$ and a $d_6 = 1.2$ ft. The sequent depth, d_7, is computed as:

$$d_7 = (d_6/2)\,[(1 + 8\,Fr_6^2)^{1/2} - 1]$$

$$d_7 = (1.19/2)\,[((1 + (8)(4.5^2))^{1/2} - 1] = 7.00 \text{ ft}$$

Next, verify the computed TRIAL sequent depth. The required sequent depth of 7.00 ft is more than the expected tailwater depth of 4.20 ft. The stilling basin must be depressed below streambed by 7.00 – 4.20 = 2.80 ft $\leq$ 3.00 ft provided by h_4. Because the difference is small, the TRIAL h_4 = 3.00 ft is acceptable: OK to continue with the expansion design.

9.A.6.18 Width

From continuity, the required TRIAL width, B_6, is:

$B_6 = Q/(d_6V_6) = 1380/((1.19)(27.86)) = 41.62$ ft
Select $B_6 = 40$ ft for simplicity

9.A.6.19 Length

The expansion length, L_E, determination will require judgment. A rigorous expansion angle analysis, possibly involving physical model studies, would result in reverse curved walls, which are considered costly for highway work where only sporadic design flood events are expected. Accordingly, a simple, straight, flared-wall expansion geometry and analysis is selected as being sufficient for the site conditions. Other site conditions might dictate a more rigorous analysis and costly construction.

Unlike the inlet, the expansion has a wide variance in values of Fr. Also, this is not a true open channel transition because the purpose of the expansion is to convert the barrel flow into hydraulic values conducive to a stable hydraulic jump.

Fr_4 is approximately 0.9, and should the flow pass through critical, the flow would be 1.0. Possibly, the flow would pass through 0.715 d_{c5} at the beginning of the expansion, Section 5, in which case a higher Fr_5 would occur or:

$d_{c5} = 0.315[(Q/B_5)^2]^{1/3}$
$d_{c5} = 0.315[(1380/10.0)^2]^{1/3} = 8.41$ ft
$0.715\ d_{c5} = (0.715)(8.41\text{ ft}) = 6.01$ ft
$V_{c5} = Q/(0.715\ d_{c5}\ B_5) = 1380/((6.01)(10.0)) = 22.96$ ft/s
$Fr_5 = V_{c5}/(gd_{c5})^{1/2} = 22.96/((32.2)(6.01))^{1/2} = 1.65$

Similar to the inlet contraction, consider an acceptable transition angle for the expansion as shown in Figure 9.A-8 to be Tan $\theta = 1/(3Fr)$.

The most conservative solution to avoid flow separation from the walls would be to use a Fr = Fr_6 = 4.5. The resulting angle, θ_{5-6}, and expansion length as shown on Figure 9.A-8, L_E, would be:

$\text{Tan}\ \theta_{5-6} = 1/(3Fr_6) = 1/((3)(4.5)) = 0.0741$
$\theta_{5-6} = 4.2^o$
$L_E = 15/0.0741 = 202.43$ ft, use 202.5 ft

A 202.5-ft expansion length is costly.

The shortest expansion where there would be a higher risk of flow separation from the walls would use an Fr_5 = 0.9, which would result in a length of:

$\text{Tan } \theta_{5\text{-}6} = 1/((3)(0.9)) = 0.3704$
$\theta_{5\text{-}6} = 20.32^o$
$L_E = 15/(0.3704) = 40.50 \text{ ft}$

As a compromise, use an average Fr or:

$Fr_{5\text{-}6} = (1.00 + 1.65 + 4.5)/3 = 2.38$
$\text{Tan } \theta_{5\text{-}6} = 0.1399$
$\theta_{5\text{-}6} = 7.96^o$
$L_E = 107.27 \text{ ft, use } 107 \text{ ft}$

The resulting $\theta_{5\text{-}6} = \text{Tan } (15/107) = 0.1402 = 7.98^o$.

What might be some of the consequences in using an L_E = 107 ft. Assume the same 85% energy recovery (see Trail Basin Depth) and that flow separates and expands at the more ideal 4.2^o angle so that the active jet width at Section 6 is approximately:

$B_6 = B_5 + 2 (L_E \text{Tan } 4.2^o) = 10 + 2((107)(0.0741)) = 25.86 \text{ ft}$

From Equation (9.A.1):

$d_6 + V_6^2/2g = d_6 + [Q^2/(B_6d_6)^2]/2g = 13.30 \text{ ft}$
$d_6 + 44.77/d_6^2 - 13.30 = 0$
$d_6 = 1.99 \text{ ft}$
$V_6 = Q/((d_6)(B_6)) = 1380/((1.99)(25.86)) = 26.82 \text{ ft/s}$
$Fr = V_6/(gd_6)^{½} = 26.82/((32.2)(1.99))^{½} = 3.35 < 4.5$

The jump would be less stable with an L_E of 107 ft. Accepting the potential consequences associated with some flow separation along the walls, use a 107-ft-long expansion having a terminal width of 40 ft straight walls and a uniform sloping floor.

9.A.6.20 Floor

The floor may either be uniformly sloped or variably sloped (ogee). First, however, some estimate of the hydraulics of the flow entering the expansion is needed. The worse case would be should flow pass through critical depth (d_{c5} = 8.41 ft) shortly before reaching the expansion (approximately 3d_{c5} upstream of expansion) and then pass through a depth of 0.715 d_{c5} = 6.01 ft at the beginning of the expansion:

Compute h_4/d_{c5} for entering Figure 9.A-9
$h_4/d_{c5} = -3/6.01 = -0.50$

From Figure 9.A-9, using Fr_5 = 1.65, obtain $L_E/(0.715d_{c5})$= 1.2 for the bottom of the nappe and 1.9 for the top:

Nappe Top — L'_E = (1.9)(6.01) = 11.42 ft which would be the impact point had this been a free overfall.

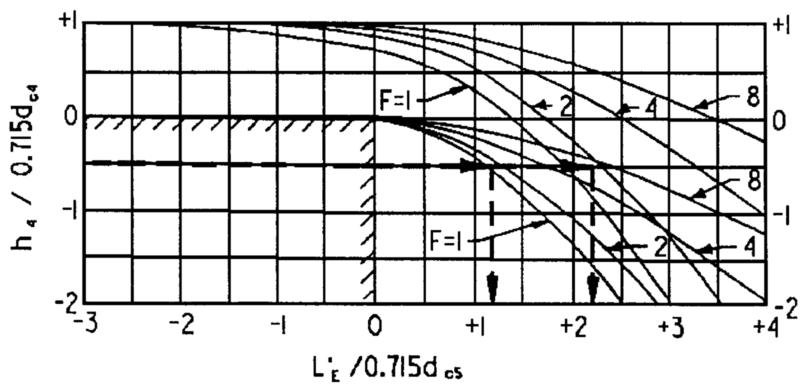

FIGURE 9.A-9 — Free Fall Nappe Geometry

Nappe Bottom — L'_E = (1.2)(6.01) = 7.21 ft < 107 ft provided indicating no vertical flow separation as shown in Figure 9.A-10.

Because the nappe length L_E = 7.21 ft to 11.42 ft is less than the provided expansion length of L_E = 107 ft, a nappe-shaped floor is not required to prevent vertical separation nor is it even possible to provide. Had the nappe impinged upon the stilling basin floor beyond L_E = 107 ft, then it would be necessary to increase the expansion length to equal L_E; this is unlikely for most highway applications.

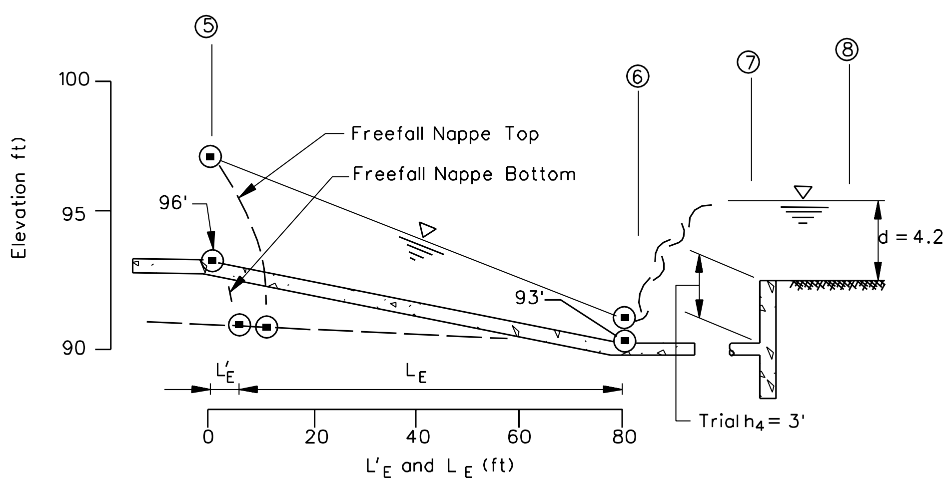

FIGURE 9.A-10 — Expansion Floor

9.A.6.21 Final Dimension Check

Where the barrel outlet is not located at an elevation equal to the stilling basin floor, then the TRIAL barrel geometry can be verified at this point in the design. Verification consists of (1) ensuring the energy grade line is compatible with the available channel profile elevations, and (2) that the previously assumed barrel length of 370 ft coupled with the inlet and outlet lengths will, in fact, all fit under the roadway template and any other required fill.

The energy grade line is computed and plotted in Figure 9.A-11. From the resulting elevations, it is found that there is sufficient fall to generate the indicated flow profile from Section 1 to Section 5.

From Figure 9.A-7, select the uniformly sloped apron inlet of which 40 ft can be placed under the fill without exceeding the structural engineer's selected 15-ft span criteria.

From Figure 9.A-8, compute the portion of the expansion that can be located under the fill without exceeding the structural engineer's selected 15-ft span criteria as ((15 − 10)/2))/Tan 7.98° = 17.83 ft.

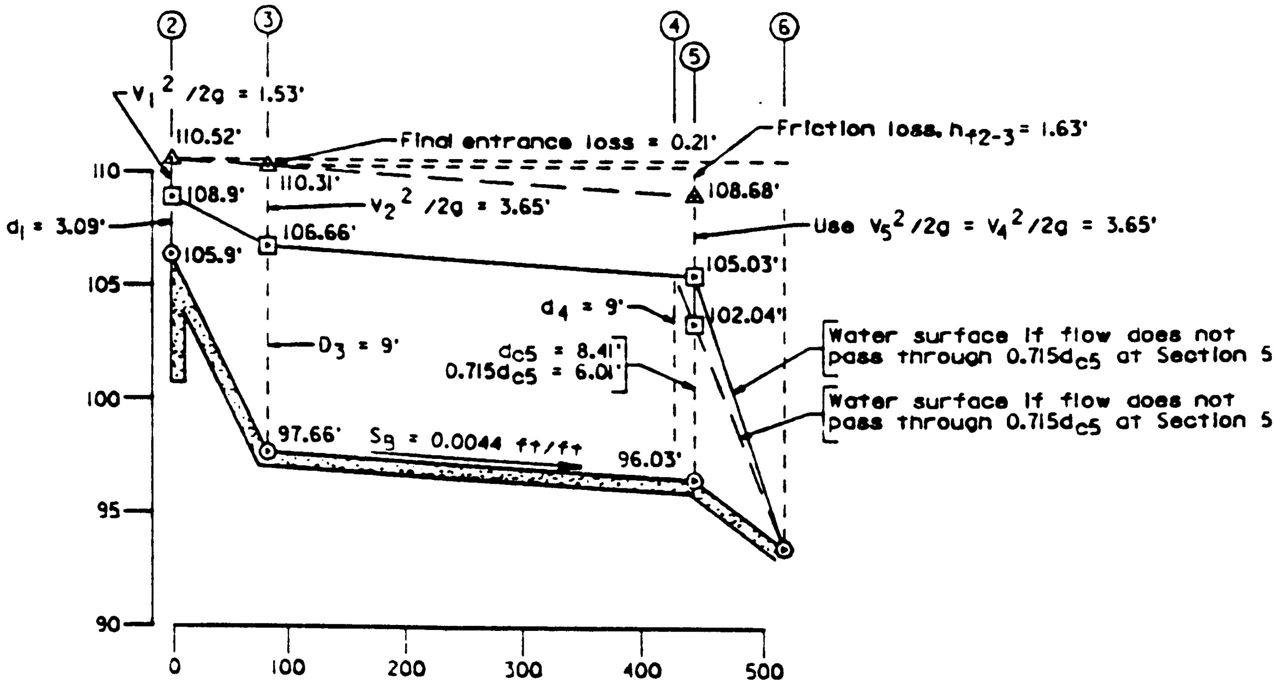

FIGURE 9.A-11 — Culvert Energy Grade Line

Plot the inlet, barrel and expansion to see if they will fit under the required fill geometry as shown in Figure 9.A-12. The 427 ft provided is sufficient to accommodate the required 426 ft template: OK to proceed with the outlet design.

9.A.6.22 Outlet Design

The width of a stilling basin for use as an outlet was necessarily determined when designing the expansion or from the Expansion Design:

$B_6 = B_7 = 40$ ft

For the USBR Type III basin of Figure 9.A-13, determine the following:

- Distance to impact blocks is:

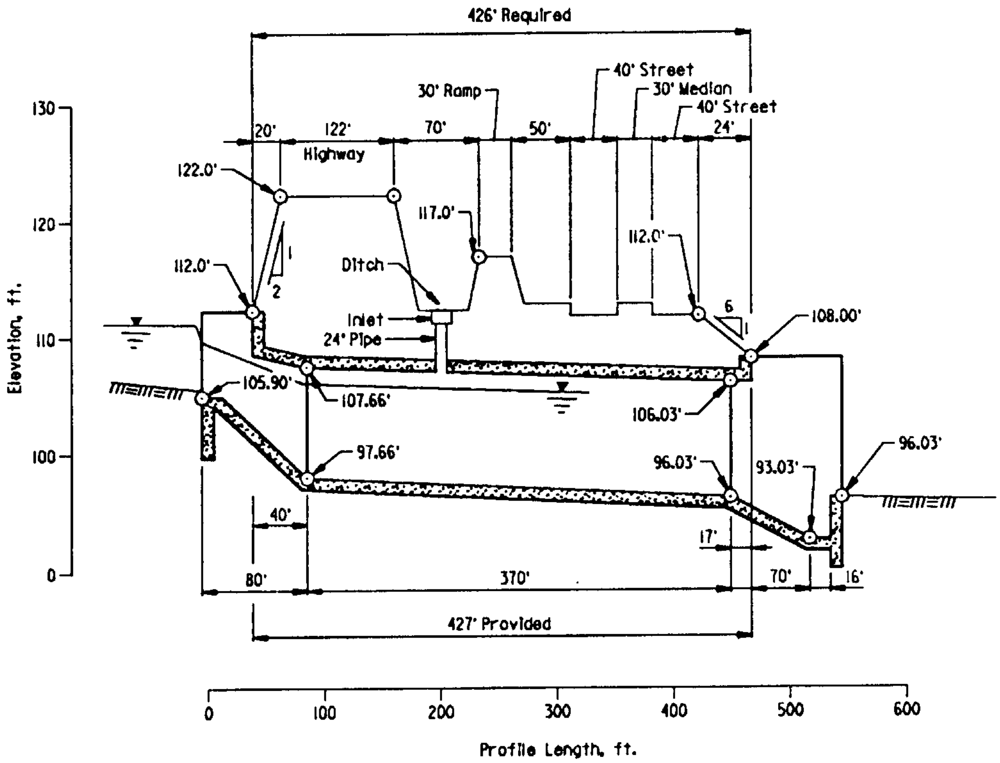

FIGURE 9.A-12 — Final Culvert Dimension Check

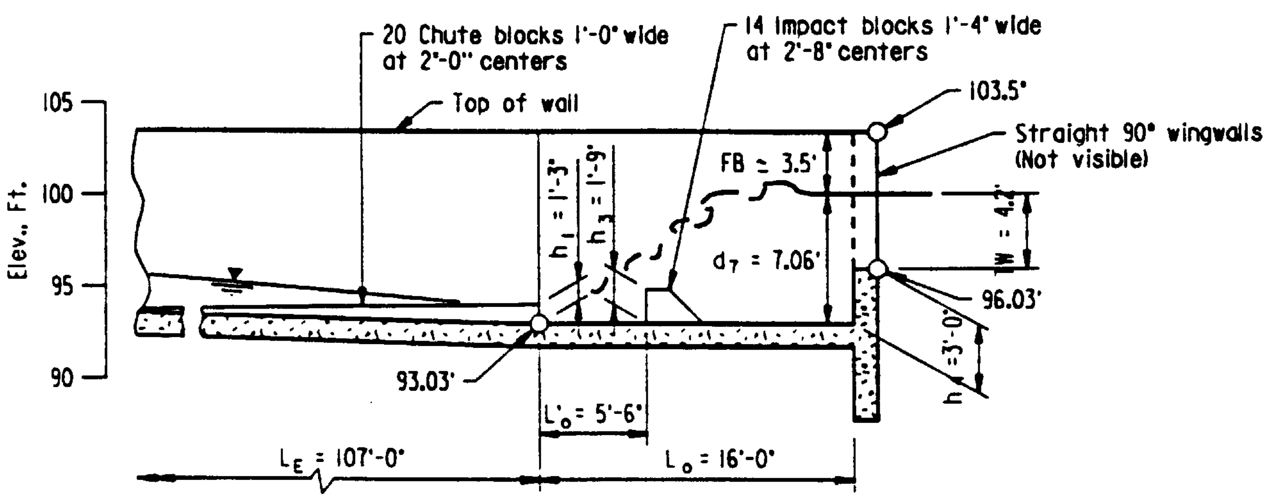

FIGURE 9.A-13 — Outlet Profile

$L = 0.8d_7 = (0.8)(7.00) = 5.60$ ft, use 5.5 ft

- Impact block height is:

  $h_3 = 1.4d_6 = (1.4)(1.19) = 1.67$ ft, use 1.75 ft

- Impact block width and spacing:

  $0.75h_1$ or $(0.75)(1.7) = 1.28$ ft, use 1.33 ft

  (Requiring 14 blocks 1.33 ft wide with 1.33 ft between blocks and 2 ft between the end blocks and the stilling basin wall).

- Chute block height is:

  $h_1 = d_6 = 1.99$, use 1.25 ft

- Chute block width and spacing, h_4:

  $d_6 = 1.19$ ft, use 1.0 ft

  (Requiring 20 blocks 1 ft wide with 1 ft between blocks and 0.5 ft between the end blocks and the stilling basin wall).

- The end sill is:

  $1.25\ d_6 = (1.25)(1.19) = 1.49$ ft, use 1.5 ft

  (Which is less than the 3 ft provided in depressing the stilling basin below streambed to obtain sufficient sequent depth: OK).

- Stilling basin length is:

  $L_o = 2.25d_7 = (2.25)(7.00) = 15.75$, use 16 ft

- Freeboard in the stilling basin is:

  $F_B = 0.1(V_6 + d_7) = 0.1(26.82 + 7.00) = 3.38$ ft, use 3.5 ft

Some culverts, particularly those with improved inlets or high-velocity inlets, may be sensitive to sediment deposition (“silting”) problems. Section 9.12 of this Chapter addresses these problems. The Example in Section 9.12.3 makes an assessment of sediment problems for this Example high-velocity culvert.

9.A.7 REFERENCES

(1) Federal Highway Administration, *River Engineering for Highway Encroachments — Highways in the River Environment,* Hydraulic Design Series No. 6, FHWA-NHI-01-004, December 2001.